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Technical Challenges for Vehicle 14V/28V Lithium Ion Battery Replacement

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ABSTRACT

Modern commercial and military vehicles are equipped with more electrical accessories and demand more power than ever before. This causes an increase in the weight of the battery as well as drives the battery to end of life when the vehicle is stationary with the engine off. Lithium ion batteries, which are known for their high power and energy to weight density, long cycle life, and low self-discharge rate, are considered to be an alternative for the replacement of existing Starting, Lighting, and Ignition (SLI) lead acid batteries. Lithium ion battery chemistry offers double the reserve time of the stock battery and a significantly greater number of charging and discharging cycles while providing weight savings. There is no acid inside a lithium ion battery to cause corrosion, which eliminates potential damage to a vehicle from chemical spills and poisonous gases. Due to the slim cylindrical nature of many lithium ion cells, the battery design can be customized in order to fit a space claim in the vehicle. However, the characteristics, including the charge and discharge control of lithium ion battery chemistries, are different from those of flooded and sealed lead acid batteries. The traditional continuous battery charging approach may potentially result in overcharge and thus raise safety concerns for lithium ion battery replacement. In addition, lithium ion batteries experience reduced battery service life when exposed to very low and deep discharge levels. These and other technical challenges of 14V/28V lithium ion battery alternatives charging/discharging control will be discussed. In addition, cost comparisons and safety considerations for different lithium ion battery chemistries for lead acid battery replacement are included in this paper. Although lithium ion battery replacement may have value for vehicle applications that have strict weight and volume requirements, and a need for increased power, their higher cost, low temperature performance, and sophisticated controls may create challenges when they are used in place of traditional vehicle SLI lead acid batteries.

INTRODUCTION

Automotive battery designers are encountering an unprecedented array of complex challenges imposed by consumer desires and government mandates. The enhanced feature content in the areas of safety, fuel economy, convenience, performance, and guidance of both commercial and military vehicles results in increased electrical power consumption, a need for larger power devices, and ultimately, higher costs. This result in battery weight increase and drives the battery to end of life when the vehicle is stationary with engine off.

Today's military and commercial vehicles are usually equipped with 28 volt and 14 volt electrical systems respectively. In the absence of major breakthroughs in vehicle electrical systems, any new load added to a vehicle will significantly modify the duty cycle to which the battery is subjected [1]. The environment in which the battery must operate has a significant impact on the battery system's design and material specifications. Severe weight, safety, cost, and size limits will be imposed on batteries in an attempt to meet increased electrical load requirements, and new battery chemistry may be introduced to reduce the weight and size of existing on-board vehicle energy storage systems. Similarly, quality and reliability levels of battery energy storage systems must undergo continuous improvement. In order to respond to these diverse and sometimes contradictory demands, new options for battery systems have to be considered as an integral part of the vehicle electrical system.

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14. ABSTRACT
Modern commercial and military vehicles are equipped with more electrical accessories and demand more power than ever before. This causes an increase in the weight of the battery as well as drives the battery to end of life when the vehicle is stationary with the engine off. Lithium ion batteries, which are known for their high power and energy to weight density, long cycle life, and low self-discharge rate, are considered to be an alternative for the replacement of existing Starting, Lighting, and Ignition (SLI) lead acid batteries. Lithium ion battery chemistry offers double the reserve time of the stock battery and a significantly greater number of charging and discharging cycles while providing weight savings. There is no acid inside a lithium ion battery to cause corrosion, which eliminates potential damage to a vehicle from chemical spills and poisonous gases. Due to the slim cylindrical nature of many lithium ion cells, the battery design can be customized in order to fit a space claim in the vehicle. However, the characteristics, including the charge and discharge control of lithium ion battery chemistries, are different from those of flooded and sealed lead acid batteries. The traditional continuous battery charging approach may potentially result in overcharge and thus raise safety concerns for lithium ion battery replacement. In addition, lithium ion batteries experience reduced battery service life when exposed to very low and deep discharge levels. These and other technical challenges of 14V/28V lithium ion battery alternatives charging/discharging control will be discussed. In addition, cost comparisons and safety considerations for different lithium ion battery chemistries for lead acid battery replacement are included in this paper. Although lithium ion battery replacement may have value for vehicle applications that have strict weight and volume requirements, and a need for increased power, their higher cost, low temperature performance, and sophisticated controls may create challenges when they are used in place of traditional vehicle SLI lead acid batteries.

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Survivability, mobility, payload, air lift capability, and offensive fire power are the vehicle design goals for military vehicles. Existing flooded and AGM lead acid batteries will not be able to fulfill new demands for energy content because of constraints on their performance, efficiency, weight, and packaging space. Therefore, replacing conventional lead acid batteries with lithium ion (Li-ion) batteries in internal combustion engine vehicles is an attractive alternative to meet immediate on-board equipment power needs.

There are many benefits to Li-ion batteries. They have high power and energy densities, a long cycle life and a low self-discharge rate; and are considered to be a potential replacement for existing Starting, Lighting, and Ignition (SLI) lead acid batteries. When compared to existing lead acid batteries, Li-ion chemistries offer two to four times the specific energy and three to ten times the number of charging and discharging cycles while also providing volume and weight savings. Because they do not contain sulfuric acid, Li-ion cells are intrinsically safe during normal operation. They will not cause corrosion and damage to a vehicle from chemical spills, nor do they generate poisonous gases. Li-ion batteries can be manufactured in cylindrical and prismatic shapes to fit within a specific space claim in a vehicle.

On the other hand, Li-ion batteries are more susceptible to overcharge and other abusive conditions that can lead to energetic thermal runaway phenomena or battery degradation. Additionally, the higher voltage of Li-ion cells can potentially present integration challenges when they are added to an existing vehicle's electrical system. Finally, harsh vehicle environment performance requirements, such as operation at extreme temperature, will likely present a technical barrier for widespread lithium ion battery replacement.

The purpose of this paper is to analyze the rationale for lithium ion battery replacement and to investigate the potential advantages of introducing this technology onto conventional military and commercial vehicles. This paper will discuss the control strategy of lithium ion batteries and the cost and safety considerations for lead acid battery replacement.

CHARACTERISTICS OF LITHIUM ION BATTERIES AND LEAD ACID BATTERIES

Lead acid batteries have been the standard in military and commercial vehicles since early of last century, but the ever-increasing demand to add power without adding weight or increasing the space claim is challenging engineers to find alternatives to lead acid batteries. One of the most promising is Liion technologies.

The development of Li-ion technology in the 1980's and 90's transformed the battery industry. Lithium ion batteries are the ideal power source for electronic equipment and are currently used in a large number of portable electronic devices such as camcorders, cellular phones, and cameras. Based upon those successes, Li-ion batteries are being developed for future electric vehicle and hybrid vehicle applications and are advantageous for multiple applications due to the high gravimetric and volumetric energy density, which is several times higher than that of lead acid batteries. Lithium-ion batteries typically consist of (i) a graphite negative electrode (anode) on a copper current collector, (ii) a lithium-containing metal oxide positive electrode (cathode) such as lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$) or lithium iron phosphate ($LiFePO_4$), on a current collector of aluminum foil, (iii) a microporous separator between the electrodes, and (iv) a liquid electrolyte that consists of a lithium salt dissolved in an organic solvent.

In addition to the benefits it offers in terms of size and weight reductions, lithium ion battery technology has many other advantages that make it ideal for vehicle batteries including:

- The battery can be produced in a shape that optimizes the space requirement.
- The system has excellent charge retention characteristics, typically retaining 85-90% of its capacity during 12 months in storage as opposed to most of lead acid batteries which exhibit 1~10% capacity loss per month, which varies depends on the manufacturer and battery chemistry.
- Li-ion technologies typically have excellent cycle life characteristics, capable of exceeding 1000 100% depth-of-discharge cycles, compared to less than 200 cycles for lead-acid batteries

- A Li-ion battery has a service-life of 10-15 years.
- Lithium ion battery technology is capable of low depth-of-discharge.
- Li-ion technologies are capable of fast charging. Normal charging can be achieved in five hours from 100% depth-of-discharge, but a one-to-two hour charge is also possible.
- The technology also lends itself to many 'smart' options, such as 'fuel gauging.'

Lead acid batteries typically:

- Have less safety hazard during charge.
- Exhibit low specific energy (Wh/kg), typically up to 30 Wh/kg for 6T format AGM lead acid batteries, which makes them too heavy for the demands of today's electric and hybrid vehicles.
- Exhibit low volumetric energy density (Wh/l), typically up to 100 Wh/l, which makes them difficult to fit in a tight space requirement .
- Have a limited cycle life.
- Generate hydrogen during the charge cycle, which means that charging cannot take place within a sealed environment.

LITHIUM ION BATTERY REPLACEMENTS FOR 14-VOLT AND 28-VOLT VEHICLE ELECTRICAL SYSTEMS

The replacement of lead acid batteries with lithium ion batteries in existing vehicle systems seems beneficial and relatively straightforward. However, it is actually very complicated due to requirements for battery control, safety, thermal management, and performance as well as overall battery and system cost. The military is working to standardize equipment for ease of fueling, performing maintenance activities like jump starting, and battery charging. Consequently, the Army has chosen a 28 volt electrical system as its standard.

Table 1 lists the automotive power system and voltage rating of power semiconductor devices [1-3]:

Table 1 - automotive power system and voltage rating of power semiconductor devices

Power systems	Battery voltage	Nominal voltage	Max operation voltage	Power device voltage rating
14V (car/light truck)	12V	14V	24V (jump start)	30-60V
28V (military vehicle/heavy truck)	24V	28V	34V (regulator failure)	75V

A 14-volt or 28-volt vehicle electrical system consists of one or more 12-volt lead acid batteries connected in series and/or parallel which are typically used to start the engine; the engine's alternator recharges the battery and provides additional power output. Lithium ion batteries can be connected in series and parallel to form a module with the required voltage. The number of cells needed is determined by the voltage level the electrical system requires. Rechargeable lithium cells usually have a nominal voltage from around 3.3 volts to 3.7 volts, limiting the choice of battery voltages to some multiple of the nominal voltage. Therefore, there will be issues with voltage matching when trying to replace a lead-acid solution with a string of Li-ion cells.

BATTERY VOLTAGE REQUIREMENTS

For 14-volt electrical systems, the battery working range is typically between 11 to 15 volts and the steady state voltage during cranking should not fall below 7.5V. For a 14-volt electrical system, modules formed with four $LiFePO_4$ lithium ion cells will likely result in a closely matched voltage. However, other types of lithium ion cells also consisting of four cells may not be suitable for a 14-volt system due to the potential for an unmatched voltage caused by the difference in nominal cell voltage. If the cell nominal voltage is too high, the battery will be undercharged which will reduce the overall energy density advantage. In addition, an undercharged battery would

not be able to provide all of its useable energy for military mission such as "silent watch." If the module is formed with less than four cells to prevent undercharge, battery charging at high voltage could easily trigger battery overcharge and result in reduced battery service life or venting and fire. Therefore, the battery charging voltage needs to be controlled properly to avoid lithium ion battery overcharge while effectively making use of all the available capacity in the battery cells.

Table 2 – Battery voltage

# of Cells	1	2	3	4	5	6	7	8	9	n
Voltage(V)	3.7	7.4	11.1	14.8	18.5	22.2	25.9	29.6	33.3	n x 3.7
Voltage range (V)	2.5-4.1	5-8.2	7.5-12.3	10-16.4	12.5-20.5	15-24.6	17.5-28.7	20-32.8	22.5-36.9	
Voltage(V) ($LiFePO_4$)	3.3	6.6	9.9	13.2	16.5	19.8	23.1	26.4	29.7	n x 3.3
Voltage range (V) ($LiFePO_4$)	2.0-3.7	4-7.4	6-11.1	8-14.8	10-18.5	12-22.2	14-25.9	16-29.6	18-33.3	

According to military vehicle standard MIL-STD-1275D, the 28V electrical circuit steady-state voltage shall be between 25VDC and 30VDC and the steady state voltage during cranking shall not fall below 16V. As with the 14-volt case, the battery cells per string need to be selected to prevent overcharging. However, string voltages can only move in discrete steps because they are dependent on a set cell-level nominal voltage as illustrated in table 2. If the constituent string has too few cells it could result in a string voltage below the maximum safe level for charging, though it would be able to make full use of its energy content. If the constituent string has too many cells, the voltage will exceed a safe range for charging and a significant portion of the energy content could be made unusable. Either scenario is not acceptable, especially in military systems where energy content is important to functionality and survivability and where safety and reliability of systems is paramount. For example, if a module is formed with eight $LiFePO_4$ lithium ion cells, the constituent string would have a voltage range of 16-29.6V. In this case, the alternator charging voltage must be carefully controlled to avoid battery overcharge; or alternatively, cells would have to be added to the string to increase the voltage which would add more mass, volume, and cost for potentially little capacity gain. For other chemistries with different nominal voltage, voltage matching may be possible with seven cells. However, military 6T packaging issues, mass constraints, and volume constraints may make this difficult to achieve using existing commercial sizes without customizing the cells. If a battery module at such a voltage could only be made into a six cell string, charging on-board a military vehicle will likely trigger battery overcharge because the maximum charging voltage of 24.6V for that string would be less than the required electrical system minimum steady state voltage of 25V.

Lead acid batteries in conventional vehicle systems are typically charged using a constant voltage floating charge method, and the charging voltage is adjusted with temperature. It is well known that lithium ion battery service life is greatly reduced if it is charged using a high floating charge voltage. A difference of 3-5 mV may cause a 5% differential in battery state of charge (SOC) for many lithium ion batteries (depending on battery charging current and temperature). A battery charging control error may lead to battery undercharge which will reduce the available lithium ion battery energy. On the other hand, improper battery charging control may result in battery overcharge which triggers hazardous conditions or reduces battery service life. Accurate battery charging voltage control will be the key to maximizing the service life and useable energy of lithium ion battery replacements in dynamic vehicle environments.

BATTERY SIZE CONSIDERATIONS

The optimization of the battery cell and system size may be another challenge. There are a wide variety of commercial sizes for lead acid batteries; and similarly, high energy and high power lithium ion battery cells come in a wide variety of sizes and formats depending on the manufacturer and intended application. The 6T size lead acid battery (10.5"x10"x8.5") is the standard size battery for 95% of military vehicle applications. In order to reduce the logistic burden and increase the standardization of energy sources in military vehicles, lithium ion battery replacements for lead acid must be the standard 6T size. Therefore, proper lithium ion cells must be chosen carefully to ensure high packing efficiency for energy content. It is especially important to consider the amount of volume and mass overhead required for battery management systems (i.e. electronic control units) within the 6T volume. If more electronics are required (including voltage and temperature sense leads), less energy content will be able to be fit into the 6T volume. Therefore, it is imperative that the battery electronics be minimized to provide space for additional cells while still providing the proper levels of control, ruggedness, redundancy, and reliability for military systems. This minimization is not a trivial task since advanced SOC estimation for lithium ion batteries will be required for more precise situational awareness of battery remaining useful life and capacity in military systems; however, these advanced SOC methods often can require additional circuitry and components. Prismatic cells may be ideal to form 6T size battery modules because of their volumetric packaging advantages.

LITHIUM ION BATTERY PERFORMANCE AT EXTREME CONDITIONS

Operating temperature can significantly affect the safety, performance and life cycle of Li-ion battery systems [4-5]. Lead acid and Li-ion batteries systems both operate reasonably well near room temperature. Generally, higher temperatures improve a battery's performance because of increased electrochemical reaction rates; however, a battery's lifetime decreases because elevated temperatures increase corrosion. If temperature uniformity can be obtained within and between modules the pack can operate closer to its desired optimum operating temperature range.

The performance of current commercial lithium ion battery technologies is sensitive to temperature with a typical operating range between 0ºC to 50ºC. At low temperatures, the impedance of Li-ion cells increases which reduces the overall available power and can adversely affect the ability to meet startup requirements. In addition, low temperature charging can also present a technical challenge as Li metal plating can occur unless charging rates are carefully controlled. In order meet startup requirements -40ºC (as required by military vehicles) and overcome Li plating during low temperature charging, a battery heater, which can be located inside or outside of the battery pack, may be needed. Such a heater can draw the energy from the battery or an outside source. Some ongoing investigations such as electrolyte additives or new electrolytes are being performed by numerous researchers to improve low temperature performance [6].

In order to satisfy users' requirements, both military and commercial vehicles have to be designed to operate in a wide range of temperatures. Military standards require vehicles to be capable of operating from -45ºC to 71ºC (-50ºF to 160ºF). Army standard R-70-38 provides the testing temperature requirement and a listing of extreme climate conditions. These requirements present a significant technical challenge for Li-ion chemistries due to their relatively narrow operation range in comparison with lead acid systems. Furthermore, operation of Li-ion batteries at temperatures >70ºC introduces potentially dangerous thermal runaway hazards and significant reduction in battery life. To optimize the performance of Li-ion systems and prevent safety hazards, a thermal management system may be required to deliver: (1) an optimum operating temperature range for lithium ion battery modules, (2) minimized temperature variations within a module for better battery management and longer service life. However, the thermal management system must be compact and lightweight, easily packaged in the vehicle, reliable, and low cost. It must also allow easy module access for servicing and use minimum power for fans and pumps.

BATTERY MANAGEMENT SYSTEM

Unlike lead acid batteries which have an inherent level of safety, lithium ion batteries are sensitive to battery over-charge and over-discharge. Therefore, a battery management system (BMS) is required [7-8]. The BMS monitors and reports on battery state of charge, state of health, voltage, current, and temperature. Additionally, the BMS is capable of bypassing charge or discharge current around a cell or cell block which has reached a pre-set voltage

limit to maintain the cell voltage at that limit or stop charge or discharge current when needed. Most BMS's have response times from several hundred milliseconds to several minutes for their shut down circuitry. This poses a danger that lithium ion batteries could be over-charged or over-discharged for short periods of time due to the potential spikes in the vehicle electrical systems. MIL-STD-1275D indicates that the spike allowed in the 28V electrical system can be as high as 250V for 70 micro-seconds and 40V for 1 millisecond. Further research is needed to study the impact of voltage spikes on BMS and battery safety as well as cycle life in the 14 or 28 volts electrical system.

One major BMS design challenge is creating the capability of handling transient spikes to prevent over-charge, over-discharge, and over-current at an affordable cost. If the transient spikes cannot be handled properly by the BMS, the potential impact on battery life and performance needs to be further studied. Additionally, BMS designs will be driven by advanced battery charging and discharging methods. For example, battery pulse charging would require the BMS to function properly with a variety of charging pulse durations and amplitudes. Additionally, the BMS should be designed and interfaced to the vehicle power management architecture to ensure proper function. The level of current required for engine cranking will require the BMS to have enough sourcing current capability while being smart enough to take care of any "over-current" issues.

Lithium ion batteries are considered to have a much lower self-discharge rate as compared to conventional lead acid batteries. However, the employment of a BMS in lithium ion batteries consumes a finite amount of energy from the battery system which will lead to a higher self-discharge rate. Therefore, the BMS must be designed to consume very little electrical energy while the battery system is not operating.

BATTERY CHARGING

Battery charging is one of the biggest challenges for the lithium ion battery replacement concept. The charge and discharge control characteristics of lithium ion battery chemistries are different from those of flooded and sealed lead acid batteries. Unlike lead acid batteries, lithium ion batteries are sensitive to battery charging voltage. The traditional continuous constant voltage battery charging approach employed in existing vehicle electrical systems will potentially result in overcharge and thus present safety concerns for lithium ion battery replacement unless the battery charging voltage is set low enough. However, low battery charging voltage will result in reduced available battery energy for missions requiring silent watch, which is problematic. In addition, lower battery charging voltage will likely increase the battery charging time required to keep the batteries fully charged.

Alternative battery charging methods such as the combination of constant current and constant voltage as well as other sophisticated charging methods may require significant changes in charging control and alternator system circuitry. This may result in packaging issues. No matter what kind of battery charging method is selected for lithium ion batteries, lithium ion battery modules cannot be used as lead acid battery replacements without modifying existing charging control systems to match the lithium ion battery charging requirement.

BATTERY COST AND WEIGHT

Unlike "lead acid" which specifies one particular type of battery chemistry, the term "lithium-ion" refers to a family of battery chemistries of which there are many varieties [9]. Each of these Li-ion battery chemistries has strengths and weaknesses with respect to the five categories of goals that must be met in order for large-scale commercialization of lithium ion battery replacements to be successful: energy, power, lifetime, safety, and cost. Table 3 lists the comparison of specific energy and energy densities for lithium ion batteries and lead acid batteries. Lithium ion batteries have much higher specific energy and energy densities than lead acid batteries. The lithium ion battery replacements for lead acid batteries will offer greatly reduced weight and size advantages while providing the same or more energy to meet vehicle needs.

Table 3 – Battery Comparison

Battery chemistry	Theoretical limit (Wh/kg)	Specific Energy (Wh/kg)	Energy density (Wh/l)	Cost ($/kWh)	Life
AGM lead acid	250	~40	80~120	100~200	100~200
Li-ion	200~400	100~200	300~550	1000~2000	600~3000

Lithium ion battery cost varies depending on the particular chemistry and manufacturer. Of all the challenges to be considered in developing a successful lithium ion battery replacement, cost may be the most uncertain and also the most critical. A generic estimate of the cost of a lithium ion battery module is about $1000/kWh which is much higher than the cost of $100-$200/kWh for lead acid batteries. The huge cost difference prevents the wide acceptance of lithium ion battery replacements for traditional vehicle applications in the near future unless this cost can be greatly reduced. Moreover, the vehicle system engineering changes to accommodate the control and packaging of lithium ion battery replacements will add other costs. The penetration of lithium ion battery replacements will likely first occur in military or high-end commercial vehicle markets which may be willing to accept higher costs for more energy, less weight, less energy storage system size, and better performance.

SUMMARY/CONCLUSIONS

Lithium-ion batteries have been a great commercial success for a variety of portable electronics applications and are making their way into EV and HEV applications due to their high cell voltage, a winning combination of energy and power, and good cycle life. Research and development of lithium ion battery modules for lead acid battery replacement is now underway for military vehicle applications. This represents a demanding research and development situation which must balance requirements for safety, environmental operating conditions, and demanding use profiles. Although lithium ion battery replacements may have value for vehicle applications that are sensitive to weight, sensitive to volume, and need increased power, the higher cost, degraded low temperature performance, and sophisticated controls for lithium ion batteries will create challenges to the successful replacement of traditional vehicle SLI lead acid batteries.

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